Micromachined Silicon Seismic Transducers

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ABSTRACT

Batch-fabricated silicon seismic transducers could revolutionize the discipline of CTBT monitoring by providing inexpensive, easily deployable sensor arrays. Although our goal is to fabricate seismic sensors that provide the same performance level as the current state-of-the-art "macro" systems, if necessary one could deploy a larger number of these small sensors at closer proximity to the location being monitored in order to compensate for lower performance. We have chosen a modified pendulum design and are manufacturing prototypes in two different silicon micromachining fabrication technologies. The first set of prototypes, fabricated in our advanced surface-micromachining technology, are currently being packaged for testing in servo circuits — we anticipate that these devices, which have masses in the 1-10 μg range, will resolve sub-mG signals. Concurrently, we are developing a novel "mold" micromachining technology that promises to make proof masses in the 1-10 mg range possible — our calculations indicate that devices made in this new technology will resolve down to at least sub-μG signals, and may even approach the 10^{-10} $G/\sqrt{Hz}$ acceleration levels found in the low-earth-noise model.

KEY WORDS

Silicon micromachining, microelectromechanical systems, bulk micromachining, surface micromachining, mold micromachining, seismic transducers, accelerometers, seismometers, CTBT.

1. INTRODUCTION AND OBJECTIVES

One of the principal factors inhibiting the effort to collect seismic data for CTBT monitoring is the sheer cost, including both the system cost and the deployment-cost, of current seismic transducers. Our motivation in pursuing microminiature silicon seismic transducers is twofold. First, such devices would be much less expensive to manufacture than current seismometers, since they could be batch-fabricated in much the same way that electronic integrated circuits are. Moreover their small size would make deployment easier and cheaper as well. Our goal is to fabricate seismic sensors that provide the same performance level as the current state-of-the-art "macro" systems, with adequate response, over a 0.01 to 100 Hz bandwidth, to the 10^{-10} $G/\sqrt{Hz}$ acceleration levels found in the low-earth-noise model. It may be possible, however, to relax the specification for the minimum resolvable signal — given the compactness of the micromachined sensor package we envision, it should be feasible to install the new sensors in much more proximate locations than can be attained with current systems.

We have calculated the best-case performance possible for a seismic acelerometer fabricated in Sandia's experimental "mold-micromachining" technology to be at or very near our most ambitious target specifications. Accordingly, we are pursuing development of this new micromachining technology. At the same time, we are manufacturing prototypes with more modest performance expectations in our much more mature "surface-micromachining" fabrication technology. These first prototypes, which have just recently been completed and have not yet

been characterized, will have nowhere near ideal performance (we expect mG resolution), but nonetheless do provide a starting point for further development of fabrication technology, mechanical designs, and servo circuits.

2. PROTOTYPE DESIGN

Because the principal axis of interest for seismic measurements is the vertical one, our basic accelerometer design consists of an unbalanced "teeter-totter" platform suspended on opposite sides by two small flexures (Figure 1). This design is a variation on the common "pendulum" design for existing seismic accelerometers, modified to allow differential capacitive pick-offs to be placed to either side of the flexures. We have chosen capacitive pick-offs rather than magnetic coil-based transducers because it is virtually impossible to make a coil in a micromachining process, while parallel-plate capacitors with very small, uniform gaps are a natural in this technology. We also discarded a third possibility, electron tunneling, which has been employed in sensitive accelerometer designs by another micromachining group,[1] because of reliability concerns and because of the 1/f noise which limits the performance of tunneling sensors at the very low frequencies which are of interest in seismic monitoring.

The signal-to-noise ratio for the motion of an accelerometer versus thermal-mechanical noise (electronic noise is not usually the limiting factor for seismic transducers) is given by

$$S / N = \sqrt{\frac{a_s^2 m Q}{4\, k_B T \omega_0}},$$

where a_s is the acceleration signal, m the proof mass, Q the so-called "quality factor" (a measure of damping), k_B is Boltzmann's constant, T the absolute temperature in Kelvin, and $\omega_o = 2\pi f_o$ the natural frequency of the mechanical system.[2] If we insert $10^{-10}\ G/\sqrt{Hz}$ for a_s, and the maximum possible Q of 30,000 (corresponding to the intrinsic material damping of a silicon device in an evacuated package), we obtain a set of pairs of $\{m, f_o\}$ which will give an adequate signal-to-noise ratio. From among these, a feasible pair is $m \geq 10$ mg and $f_o \leq 1$ Hz. In order to achieve these values, it will be necessary to develop a new silicon micromachining technology, as current technologies cannot deliver the combination of large (on this scale at least) proof mass and soft suspension. We have invented a novel fabrication process which may well address these issues — this new "mold" process is described below.

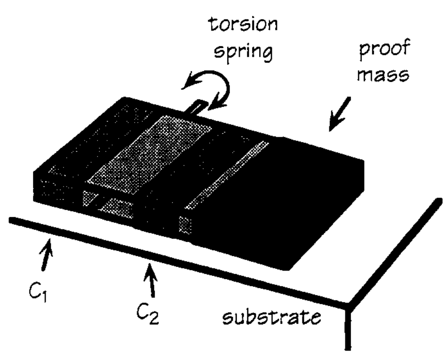


Figure 1. "Teeter-totter" seismic sensor concept.

3. SILICON MICROMACHINING TECHNOLOGIES

Silicon micromachining technologies can be divided into three categories — so-called "bulk," "surface," and "mold" micromachining. "Bulk" micromachining generally refers to processes involving wet chemical etching of structures formed out of the silicon substrate and so is limited to fairly large, crude structures. "Surface" micromachining allows patterning of thin films of polysilicon and other materials to form intricate but essentially two-dimensional layered parts (since the thickness of the parts is limited by the thickness of the deposited films). In "mold" micromachining, the mechanical part is formed by filling a mold which was defined by photolithographic means. Historically micromachining molds have been formed in some sort of photopolymer, be it with x-ray lithography ("LIGA") or more conventional UV lithography, with the aim of producing piece parts. Recently, however, several groups including ours at Sandia have independently come up with the idea of forming the mold for mechanical parts by etching into the silicon substrate itself. The following is a quick review of these three micromachining methods intended to clarify the approaches we have taken in fabricating seismic sensor prototypes. Note that the references given here are only examples and are not by any means intended to be a complete survey of the literature.

3.1 Bulk micromachining

The term "bulk" micromachining literally refers to the process of making a mechanical structure out of the bulk material (i.e. the single-crystal silicon substrate). Generally the mechanical structure is formed either by doping-selective[3] or crystallogaphic[4] wet chemical etching. These processes are relatively large-scale and crude compared to the sub-micron photolithographic processes common in microelectronic fabrication, with dimensional variations on the microns to hundreds-of-microns scale. A subcategory of bulk micromachining which offers finer dimensional control is dry etching of mechanical structures — again, the part is formed from the single-crystal silicon substrate itself.[5] One of the major advantages of bulk micromachining is that it is relatively easy to fabricate large masses (for accelerometers, for example), but, on the other hand, delicate, sensitive suspensions are difficult to realize. Also, bulk micromachining processes are not particularly compatible with electronics, simply because they aren't planar.

We rejected bulk micromachining as a fabrication strategy for seismic sensors, even though the most sensitive silicon accelerometers to date have been made this way,[1] for several reasons. First, we do not have a mature bulk-micromachining technology at Sandia, and therefore making the prototypes using bulk processes would not leverage well with our other projects. Second, bulk micromachining does not lend itself to integration with electronics and we are convinced that integrated amplifiers and servo electronics will be necessary in order to achieve the sensitivities required for treaty monitoring.

3.2 Surface micromachining

Surface micromachining uses the planar fabrication techniques common to the microelectronic circuit fabrication industry to manufacture micromechanical devices. The standard building-block process consists of depositing and photolithographically patterning alternate layers of low-stress polycrystalline silicon and sacrificial silicon dioxide. As shown in Figure 2, holes etched through the sacrificial layers provide anchor points between the mechanical layers and to the substrate. At the completion of the process, the sacrificial layers, as their name suggests, are selectively etched away in hydrofluoric acid (HF), which does not attack the silicon layers. The result is a construction system consisting of one layer of polysilicon which provides electrical interconnection and one or more independent layers of mechanical polysilicon which can be used to form mechanical elements ranging from a simple cantilevered beam to complex systems of springs, linkages, mass elements, and joints. Because the entire process is based on standard integrated-circuit fabrication technology, hundreds to thousands of devices can be batch-

fabricated on a single six-inch silicon substrate.

Because surface micromachining takes advantage of the advanced manufacturing processes developed in the microelectronics fabrication industry, it offers the same high degree of dimensional control found in electronic integated circuit fabrication, and is the micromachining method most compatible with integrated electronics.[7] The planarity which makes surface-micromachined parts relatively easy to integrate with microelectronics, however, is also the major limitation of surface micromachining — that is, surface-micromachined parts are essentially two-dimensional (since the thickness of the parts is limited by the thickness of the deposited films), and therefore relatively light and compliant. (Typical masses for surface-micromachined components are in the μg range and it is difficult to achieve natural frequencies below 1 kHz.)

Sandia's three-level polysilicon process is the world's most sophisticated surface-micromachining technology, and promises soon to offer integrated electronics as well as complex mechanical parts, so despite the difficulty of manufacturing a large proof mass in a surface process, we decided to begin by fabricating our initial seismic transducer prototypes in this surface-micromachining technology.

3.3 Mold micromachining

The principal advantage of all mold micromachining processes are that they make it possible to fabricate high-aspect-ratio parts (i.e. thick relative to surface dimensions). Mold micromachining has generally been used to manufacture piece parts (e.g. gears, etc.), although micromachined structures formed with thick photo-sensitive polymer molds have also been integrated with previously fabricated electronic circuits. Variations on the mold concept include, on the one hand, the well-known "LIGA" process, in which lithography is used directly to form a photoresist mold, and, on the other hand, silicon mold processes, in which the mold is formed by etching into the silicon substrate.

3.3.1 "LIGA" and "LIGA-like" processes

"LIGA" is a German acronym which refers to "lithography, electroplating, and injection molding". The original LIGA process, while it achieves impressive aspect ratios,[8] has only seen scat-

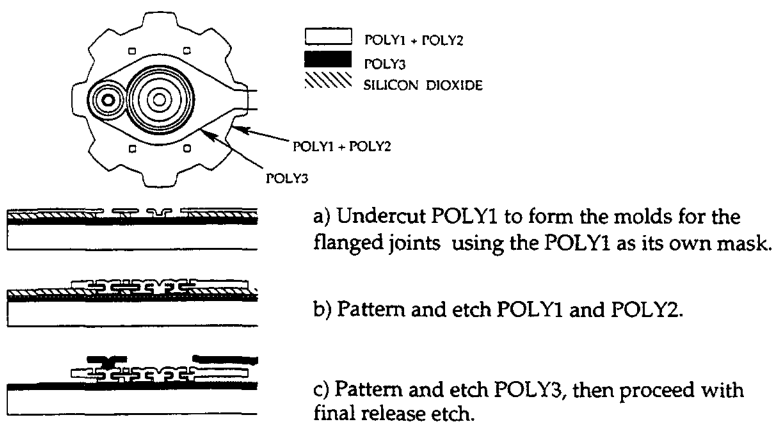


Figure 2: Example surface-micromachining process.[6] These are cross-sections through essential elements of the Sandia microengine gear and joints taken at three stages of completion.

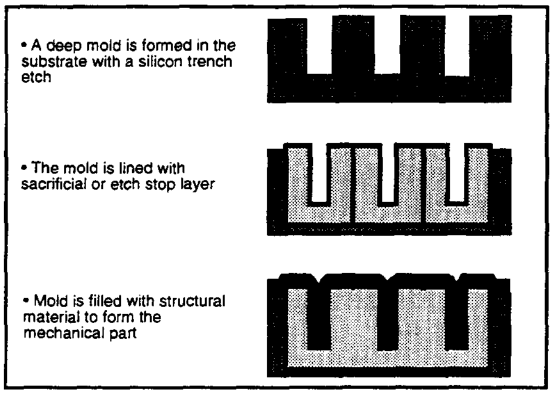


Figure 3. Generalized silicon mold process.

tered application because it requires specialized x-ray lithography equipment. "LIGA-like" processes include ones where the more common UV-exposed photoresist is used instead. These "LIGA-like" processes allow fabrication of thicker parts than can be made using surface micromachining, but are generally limited to much less extreme aspect ratios than the original LIGA process.[9] Both the original LIGA process and the "LIGA-like" processes lend themselves primarily to the fabrication of piece parts which require subsequent assembly into a microelectromechanical system.

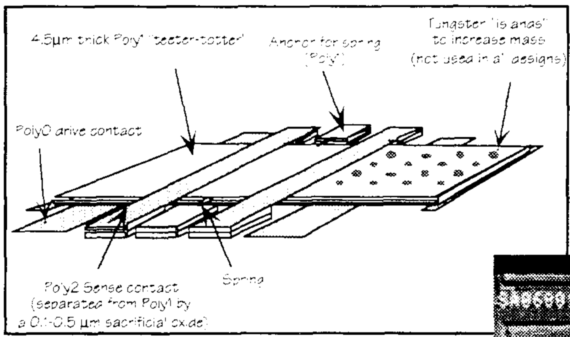
3.3.2 Silicon mold processes

The basic concept behind silicon mold processes is that the mold for a micromechanical part is formed by etching into the silicon substrate (Figure 3). Silicon mold processes thus take advantage of the fact that, by etching a high-aspect-ratio mold (that is, one which is much deeper than it is wide) and filling it with a conformal thin film, one can form a mechanical structure that is much thicker than the maximum thickness of the deposited film itself. Our group at Sandia is one of three research groups which have independently conceived of the silicon mold idea and have been pursuing variants on the basic process.[10]

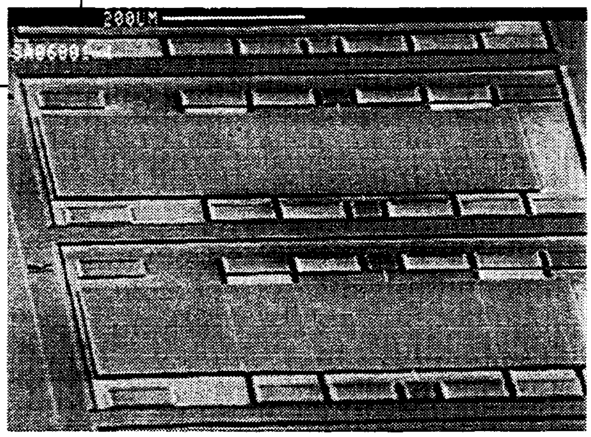
3.3.3 The Sandia mold micromachining process

The first step in the Sandia mold process is to etch the mold pattern into the substrate using a "deep trench" reactive-ion-etching process. The silicon pattern is then transformed into a mold in one of several ways. For example, if the structure will be formed of polysilicon and released in HF, the mold is oxidized at this point. It is also possible to remove the silicon mold by wet etching the silicon, in which case the mold is completed instead by depositing an etch stop layer. The commonality in both cases is that, in the end, the mold-micromachined parts are anchored to the substrate and released in place, like surface-micromachined parts — the mold is not reused. After the mold is formed, it can be filled with any of a number of materials, including most of the thin films common in the semiconductor industry (doped or undoped polysilicon, silicon nitride, CVD tungsten, etc.), as well as plated metals. The wafer is then planarized by an etchback or chemical-mechanical polish (CMP) process. At this point, assuming materials compatibility, it can be taken through a surface-micromachining or electronic integrated circuit fabrication process (or both). Once all the processing is complete, the mechanical parts are released so that they are free to move relative to the substrate.

This experimental process would be ideal for manufacturing seismic sensors because it offers



← Figure 4a. Conceptual sketch of surface-micromachined seismic sensor prototype.



→ Figure 4b. SEM photo of surface-micromachined seismic sensor prototype. These first prototypes have only one set of differential capacitive contacts, which will be used for both pick-off and forcing.

increased mass while retaining the ability to fabricate a compliant suspension. Accordingly, we are currently working on a version of the process which will provide a proof mass several orders of magnitude larger than is possible with surface micromachining and will also offer a compliant surface-micromachined suspension and the possibility of integration with electronics.

4. PRELIMINARY RESEARCH RESULTS: SURFACE-MICROMACHINED PROTOTYPE

We have designed and fabricated prototype seismic accelerometers in Sandia's state-of-the-art surface-micromachining process (see Figure 4 for a conceptual sketch and SEM photo). Again, this prototype design is a modified pendulum, in which differential capacitive sense pick-offs and forcers are positioned on either side of the torsional springs. The first lot of prototypes is completed, has passed basic functional testing, and is currently being packaged for insertion in a force-feedback circuit for more thorough testing. This first lot of prototypes has only one set of contacts (the lower set shown in Figure 4), and so will be tested using a charge-control servo circuit developed by Litton Guidance and Control Systems (Woodland Hills, CA), which uses one set of contacts for both signal pick-off and force-feedback. Subsequent prototypes will have separate pick-off and forcer contacts, so it will be possible to test them using modified Sandia voltage-control navigational servo circuits. We expect these surface-micromachined prototypes to resolve signals in the mG to μG range.

5. PRELIMINARY RESEARCH RESULTS: MOLD-MICROMACHINED PROTOTYPE

Concurrently with the surface-micromachined prototype fabrication effort, we are developing the capability to make heavier proof masses using the silicon mold technology described in Section 3 above. As a first attempt at a mold-micromachined seismic sensor prototype, we fabricated a molded tungsten proof mass by oxidizing a trench-etched silicon mold, and filling it with metal. Figure 5a shows the etched mold after oxidation. In order to form this mold, we used a $Cl_2/HBr/O_2$ etch chemistry in an electron cyclotron resonance (ECR) reactive-ion etcher to etch pillars roughly one micron in diameter and over twenty microns tall out of the silicon substrate. We then oxidized the wafer to an oxide thickness of 1.5 microns. Finally, we filled the mold with chemical-vapor deposited (CVD) tungsten and planarized the wafer with CMP. Figure 5b shows

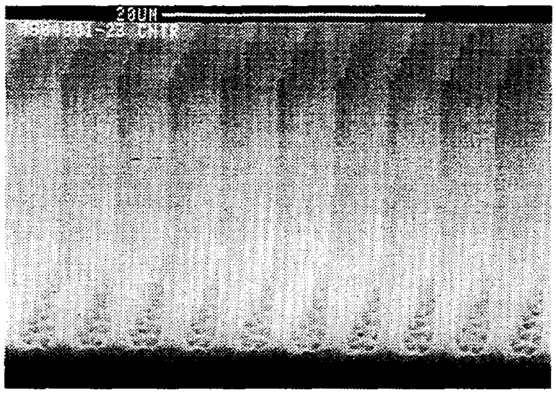


Figure 5a: Silicon dioxide mold for accelerometer proof mass.

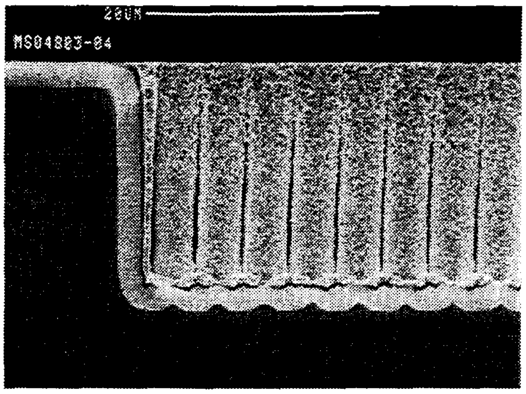


Figure 5b: Molded tungsten proof mass.

the finished proof mass ready to be integrated with surface-micromachined suspension springs and sense contacts before being released in a hydrofluoric acid etch.

6. FUTURE PLANS

Our future plans for the surface-micromachining prototype effort are to servo the present prototypes, and to continue improving the design, leading to more sensitive prototypes. Concurrently, we plan to continue development of the silicon mold process — we expect that the mold process will ultimately yield stand-alone seismic sensor prototypes which, when servoed, will resolve better than 1 $\mu G/\sqrt{Hz}$ signals.

Once we have manufactured discrete sensors with good performance, we plan to turn to the challenge of integrating parts of the servo circuitry on-chip with the sensor. Integrated electronics will increase the performance of the sensor by reducing stray-capacitance problems, and will reduce the size of the overall system as well.

7. SIGNIFICANCE FOR CTBT

Inexpensive micromachined silicon seismic sensors could revolutionize the seismic data-gathering process. The cost savings realized by a micromachined design would result not only from the reduced cost of the sensor itself, but also from lower installation and maintenance costs. A borehole system using current sensor and electronics technologies can be as heavy as 200 pounds (90 kg) and its installation requires a drilling rig. The expense of installing and maintaining an array of such sensors often far outweighs the cost of the sensors themselves. A small, low-cost sensor could also make portable/disposable systems for both cooperative and non-cooperative seismic monitoring viable.

The capabilities and cost of the proposed seismic sensor would also make it attractive for related commercial applications such as low-cost, sensitive earthquake monitors and sensors for oil and gas exploration. The existence of large commercial markets for the sensor would drive manufacturing volumes up and costs down and would attract the interest of commercial sensor manufacturers. The CTBT community, which is in itself a relatively small market, would then benefit from association with these larger commercial applications.

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